WELDING RESEARCH

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The Influence of Working Fluid Physical Properties on Weld Qualification for In-Service Pipelines

The effect of working fluid properties on test weld cooling rates for weld procedure qualification for active pipeline welding was investigated

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ABSTRACT. Welding on in-service pipelines (hot tapping) has been practiced for many years on pipes containing both liquids and gases. The increasing frequency of sour conditions within gas and oil pipelines increases the risks involved in welding on pressure-containing lines and imposes additional restraints in the form of maximum tolerable hardness, especially in the heat-affected zone (HAZ). While there are existing procedures to deal with the cooling rate effects of the liquid or gas contained within a pipeline, little is known of the effects of the physical properties of the liquid or gas on the cooling rates to be expected. Most experimental work on procedure verification has been done on still or circulating water as the working fluid.

In this study, a pressurized test coupon of X-52-type pipe was filled with liquids of differing physical properties — water, ethylene glycol, methanol, water-glycol mixtures and water-methanol mixtures. Thermocouples monitored inside wall-temperature changes caused by mechanized GTAW autogenous fusion runs on the pipe surface, and optical pyrometer measurements were used to assess outside wall temperature cycles.

The results show both the working fluid physical properties and the pipe pressure conditions affect the weld zone cooling rate to a significant degree. It is possible to control cooling rates on the inside and outside walls of the pipe by adjusting working fluid properties and internal pressure conditions.

Low-hydrogen SMAW deposits were compared to the autogenous GTAW runs for limited but practical repair procedural conditions. This showed the expected heat input increase due to more efficient SMAW arc conditions is about 25%. This difference is somewhat lower than the usual GTAW/SMAW arc efficiency comparisons in the literature. It indicates the necessity for more trials incorporating the range of welding process parameters to be considered in evaluating the working fluid cooling characteristics.

Once the heat input relationships for various processes are established, the cooling rate control possible with various working fluid compositions can be utilized to assess procedure qualification in a controlled engineering environment. A procedure qualification involving the modified water-ethylene glycol working fluid has been used to make a nozzle to pipe weld on an active sour gas pipeline during the Canadian winter.

KEY WORDS

Pipe Welding
In-Service Welding
Hot Tap
Sour Service
Low-Hydrogen SMAW
Autogenous GTAW
Hydrogen Cracking
HAZ
Cooling Rates

Introduction

Branch connections to existing hydrocarbon pipelines are often attached by welding on the pipe while liquid or gas products are contained in or flowing in the pipe. This procedure is called hot tapping. The working fluid usually produces a rapid cooling rate in the weld zone, which raises concerns about possible hydrogen-assisted cracking (HAC) in the HAZ. Experience has shown that HAC can be minimized by controlling the maximum hardness in the HAZ to 350 HV for the majority of hot tapping situations. This hardness level is more difficult to achieve on older pipelines due to higher carbon levels in the steels. The carbon equivalent (CE) is therefore high as well. In sour service conditions, the maximum tolerable hardness is usually limited to 248 HV, based on provisions in NACE MR0175. Canadian Standard CSA Z-662 (Ref.1) requires qualification for both procedures and welders be based on producing a weld zone cooling rate at least as severe as that on the specific operating pipeline to be welded. Procedure and welder qualification tests are usually conducted on sections of pipe containing flowing water. This is generally an over-conservative approach due to the use of a more severe heat sink than would usually be en-

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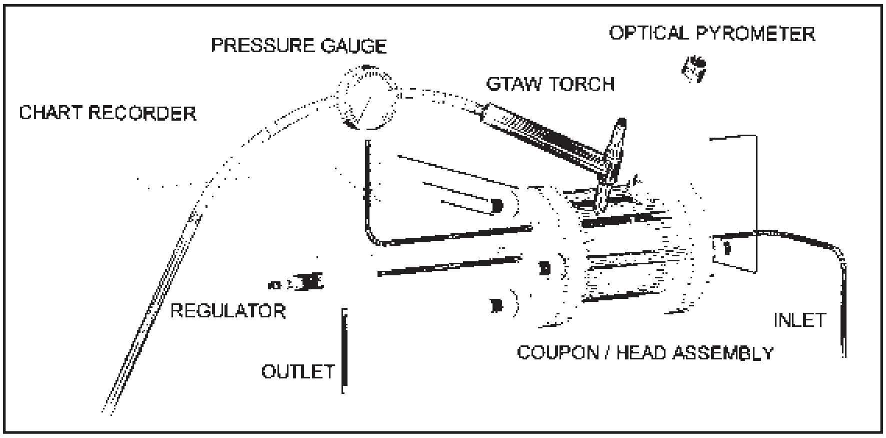

Fig. 1 — Pressurized pipe test assembly.

Table 1 — Typical Steel Chemistries

Steel	%C	%Mn	%Si	%S	%P	% other
A 106B	0.30	0.29 1.06	0.10 min	0.058 max	0.048 max	—
X 52	0.31	1.1	0.04	0.028	0.052	0.04Cr, 0.04Ni

countered in a pipeline containing flowing hydrocarbon gases or liquids. The high-quench rates inherent in this approach have caused problems in meeting specified hardness levels during procedure qualification for older pipeline steels, which tend to have higher carbon and carbon equivalent levels. The ability to control test coupon cooling rates to those representative of welding on active pipelines would help in producing more realistic procedure qualification.

Prediction of cooling rates can be accomplished by computing an expected cooling rate from welding parameters and heat-sink simulations (the Battelle approach) or by experimentally measuring heat-sink effects on cooling rates for the actual in-service pipeline to be welded (the Edison Welding Institute [EWI] approach). There has been some progress on integrating the two approaches (Ref. 2).

The integrated EWI and Battelle method allows for precalculation of expected weld zone cooling rates (Battelle) and validation via relatively simple cooling time measurements (EWI). However, there are admitted shortcomings, including a limited range of wall thicknesses for valid results and a lack of data on the effects of working fluid physical properties and internal pressure.

Another problem in using flowing water results from the necessity to find a qualification procedure that provides an acceptable HAZ hardness in the qualification test without using a welding heat input that may cause melt through of the pipe wall in a field repair. This is especially difficult on steels of high carbon and CE levels.

This project was undertaken to determine if weld zone cooling rates produced by pressurized qualification coupons containing various working fluids could be varied in a controlled manner, thereby offering more control over cooling rates and consequent hardness levels in the weld zone. The primary variables investigated were the effects of working pressure and the physical properties of the working fluids, such as thermal conductivity (or diffusivity) and liquid boiling temperatures (T_{sat}).

Experimental Results

The pressurized pipe welding test coupon assembly is shown in Fig. 1. The section is 4-in. Schedule 40 pipe (0.237-in. wall thickness), 150 mm (6 in.) long, encapsulated with machined cylinder heads. The material is ASTM A106 Grade B, which is a reasonable simulation of older X-52 pipeline steels. Comparative chemistries are given in Table 1. The differences are mainly in the Si levels as 106B is a fully killed steel, while X-52 grades are not.

Gaskets in gasket grooves machined into the heads prevented leakage, while three sections of threaded rod provided restraint for pressure application. Pressures of up to 7 MPa (~1000 lb/in.^{2}) were

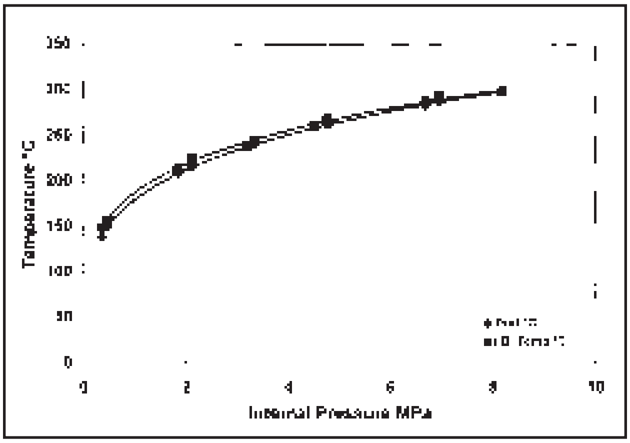

Fig. 2 — Pipe inside wall temperature and T_{sat} vs. pressure for water (1.1 and 1.65 kJ/mm).

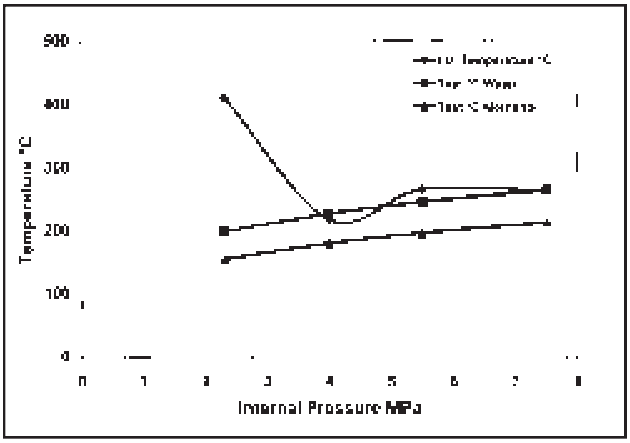

Fig. 3 — Pipe inside wall temperature for 50% methanol in water (1.45 kJ/mm) and T_{sat} (methanol and water) vs. pressure.

possible in the test assembly. Thermocouples for internal wall temperature measurements were inserted through 6.4 mm (¼ in.) NPT plugs sealed with epoxy resin, which were secure to a pressure of 28 MPa (4000 lb/in.^{2}). Pressure was applied via a hydraulic pump. Pressure rises during welding due to working fluid heating were controlled by a pressure regulator valve set to a maximum of 8.4 MPa (1200 lb/in^2). This arrangement managed the pressure variations adequately but was inconsistent in producing a repeatable pressure set point.

Weld passes on the outside wall of the pipe were conducted with a mechanized GTAW process using argon shielding gas at a flow rate of 30 L/min (15 ft^3/h) and direct current on electrode negative polarity (DCEN). This process and method were adopted to ensure consistent heat input results and avoid the complications of metal transfer and fume on optical pyrometry. Welding speed was always 100 mm/min (4 in./min). Two thermocouples were attached to the inside surface of the pipe wall directly beneath the weld zone near the center of the coupon, and their output was recorded on a digital strip chart recorder. Outside surface temperatures were monitored with an infrared pyrometer with the output recorded on a digital strip chart recorder.

Some of the variability in cooling rates experienced by welds is due to the efficiency of heat transfer as it varies from process to process, as well as during the application of a field weld with a given process. To assess the different heat transfer characteristics of the usual SMAW deposits using E7018-1 (CSA E48018-1) electrodes compared to the autogenous GTAW fusion runs used in the working fluid experiments, welds were made on a 25-mm (1-in.) diameter rod 120 mm (4.63 in.) long. The bar was surrounded with insulation to minimize heat loss during welding and contained within a sectioned 50-mm (2-in.) diameter Schedule 40 steel pipe. GTAW runs were made with a 3.2-mm-diameter EWTh-2 electrode reground to a 45-deg taper after each use. The SMAW electrodes were 2.5 mm (³⁄₃₂ in.). Similar nominal heat inputs were used for both processes. The heating and cooling cycles and the peak temperature were monitored with a K-type thermocouple embedded in the steel rod. Process efficiencies (net heat transferred) were calculated using the following relationship:

$$\Delta H = m \cdot \int_{T2}^{T1} C_P \cdot d$$

This calculated value was compared to the nominal heat input to assess process efficiency. The actual heat input is important in determining cooling rates, and, therefore, a knowledge of the heat transfer efficiency of different welding processes is critical for comparing results obtained with differing processes. The welding conditions used and the efficiency calculation results are shown in Table 2. The slightly high voltages in the SMAW process were due to a longer arc length than normal due to the restricted access permitted by the insulation surrounding the calorimeter specimen. In real procedure qualification, the actual process and heat input conditions chosen for the proposed hot-tap operation would be used.

Tests on the pressurized pipe section began with axial GTAW passes using pure water as the working fluid. Inside wall surface temperature rose in step with internal pressure at a given heat input and was very close to the T_{sat} for water, as shown in Fig. 2. Changes in heat input over the range of 1.1 to 1.65 kJ/mm had no measurable effect on this result. Pure ethylene glycol produced a large and uncontrollable temperature rise on the inside wall due to film boiling. Testing with pure methanol was not attempted due to flammability risks and the assumption that film boiling would occur at very low heat input due to a low T_{sat}. A 50% mixture of methanol in water exhibited intense film boiling behavior and high inside wall temperatures at a pressure of less than 3 MPa, but behaved as water at pressures above 3 MPa — Fig. 3. This indicates water controlled the behavior in the mixture at moderate pressures and above. Methanol experiments were discontinued at this point, since the methanol-water mixtures could not alter the behavior of the system favorably in comparison with water alone.

Evaluation continued with a 50% mixture of ethylene glycol in water. The peak inside wall temperature response indicated that with heat inputs of 1.4 kJ/mm (35 kJ/in.) and 2.1 kJ/mm (50 kJ/in.), the response in the mixture fell between T_{sat} results for the individual liquid components and that peak tem-

Table 2 — Heat Input Verification Data

Weld	Volts	Amperes	Weld Speed mm/s	Arc Efficiency Calculated %
SMAW Run 1	29	90	1.7	75.2
SMAW Run 2	27	85	1.7	85.1
GTAW Run 1	12	219	1.7	61.5
GTAW Run 2	12	219	1.7	61.5

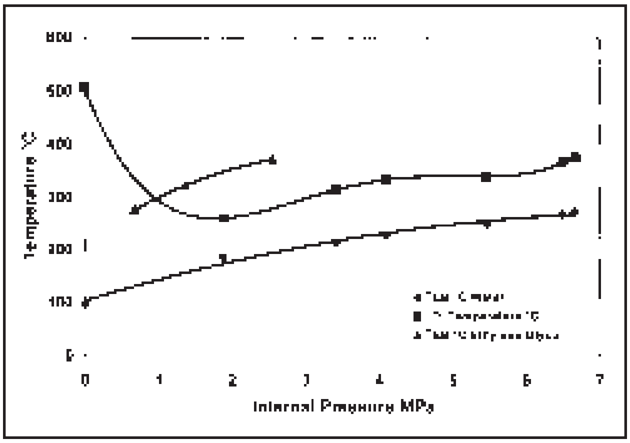

Fig. 4 — Pipe inside wall temperature for 50% ethylene glycol in water (1.4 kJ/mm) and T_{sat} (ethylene glycol and water) vs. pressure.

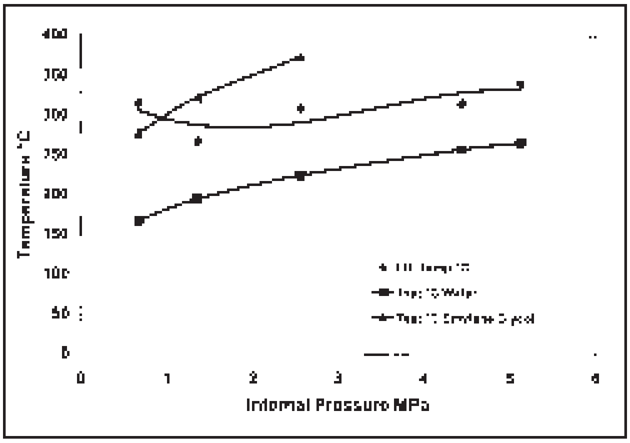

Fig. 5 — Pipe inside wall temperature for 50% ethylene glycol in water (2.0 kJ/mm) and T_{sat} (water and ethylene glycol) vs. pressure.

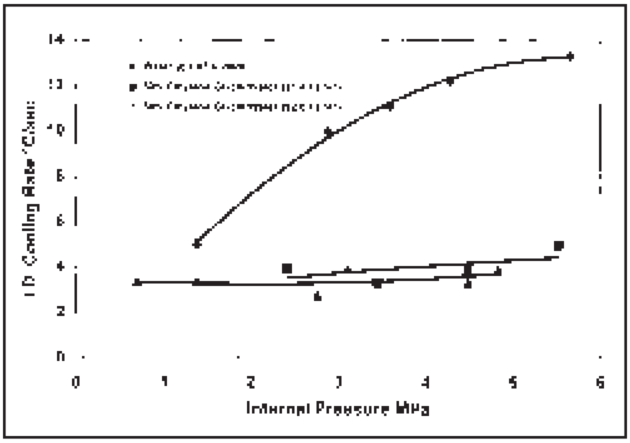

Fig. 6 — Inside wall cooling rates for water (1.65 kJ/mm) and 50% ethylene glycol in water (1.4 and 2.0 kJ/mm).

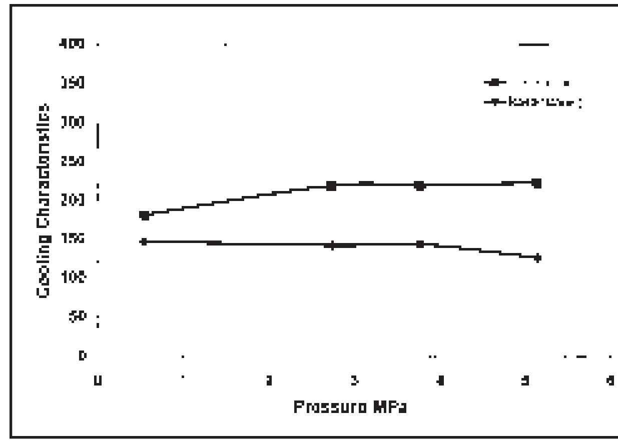

Fig. 7 — Outside wall cooling rates for water (1.4 kJ/mm).

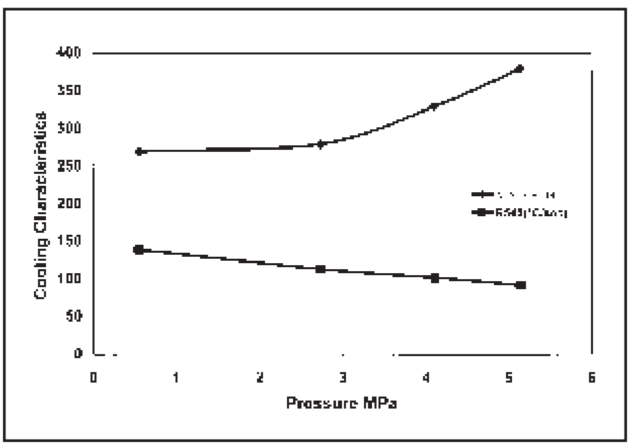

Fig. 8 — Outside wall cooling rates for 50% ethylene glycol in water (1.4kJ /mm).

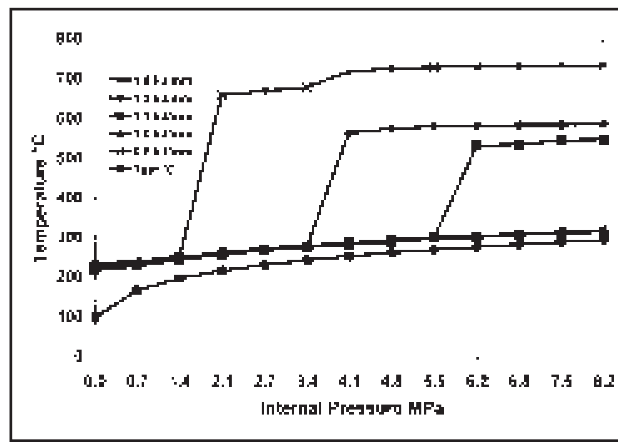

Fig. 9 — Simulated effect of heat input on pipe inside wall temperature with boiling transition in water (Battelle program).

perature increased with pressure — Figs. 4 and 5. At low pressure, film boiling caused deviations from this behavior, with steep rises in inside wall temperature observed, as occurred in the methanol experiments.

Cooling rates for the inside wall were established by initiating temperature change measurements in the first five seconds after nucleate boiling (as defined by cessation of rapid fluctuations in thermocouple output) had stopped. The results are shown in Fig. 6 for water at a heat input of 1.65 kJ/mm and for the 50% glycol mixture at heat inputs of 1.4 and 2.1 kJ/mm. The cooling rate on the inside wall in water is high and increases with pressure, while the cooling rate in the 50% glycol mixture is lower and almost invariant with pressure over a range of heat input. The inside wall cooling rate for the glycol mixture at all pressures decreases slightly as heat input increases.

Outside wall cooling rates were determined for the same conditions by recording the optical pyrometer output to determine both $\Delta T_{8\text{-}5}$ (seconds to cool from 800 to 500°C) and R_{540} (cooling rate in degrees per second at 540°C [1000°F]) values, shown in Figs. 7 and 8. It is apparent that outside surface cooling rates under either criterion decrease a small amount with water as pressure increases. With the water-glycol mixture, the cooling rate decreases significantly as pressure increases, which offers the possibility of control over the cooling rate for hot tapping weld procedure qualification testing.

Discussion

A hot-tap weld zone can essentially be regarded as a small hole through which heat is forced through the pipe wall and then removed by the working fluid. Heat transfer by the liquid experiences five defined regimes (Refs. 3, 4). When the temperature of the liquid contacting the interior pipe surface is lower than the T_{sat}, no boiling takes place, and heat transfer is low and via natural convection. As the temperature of the liquid in contact reaches the T_{sat}, bubbles are nucleated at the pipe surface and condense quickly, as the bulk liquid temperature is below T_{sat}. The bubbles increase the rate of heat transfer by stirring the liquid next to the pipe wall. This is subcooled nucleate boiling. When the bulk liquid temperature reaches T_{sat}, bubbles are larger and migrate within the liquid. Heat transfer rates continue to rise in this nucleate boiling regime until the departure from nucleate boiling (DNB) occurs at a critical heat flux. Heat transfer rates then decrease rapidly due to vapor films forming on the pipe wall surface, which limits possible heat transfer in the liquid phase. This is the transition boiling regime. Liquid wetting is progressively eliminated and heat transfer is then controlled mostly by gaseous heat transfer, which is less efficient, and it becomes even less efficient as the gaseous layer thickens as heat input increases. The result is increasing inside-surface pipe wall temperatures. Finally, when the temperature difference between the pipe wall and the liquid rises even more, a continuous vapor film is formed on the pipe wall in the film boiling regime. The heat flux again rises due to thermal radiation from the pipe wall, which experiences an ever-increasing temperature difference from the working fluid. Ultimately, the pipe wall will reach the melting temperature of the material and failure occurs.

The hot tap program from Battelle assumes this separation of the pipe wall from the working fluid occurs at relatively low heat inputs, as shown by the rapid jumps in inside-wall temperature in Fig. 9. This study shows that the actual situation is less than the sudden transitions predicted in computer simulations and that the rate of heat transfer is also controllable. With water as a working fluid, inside-wall temperature does indeed rise with pressure, but no film boiling occurs except at atmospheric pressure and moderately high heat input. This is demonstrated by the lack of adherence of the inside surface temperature to the T_{sat}. At higher pressures, only a small amount of nucleate boiling (small fluctuations in thermocouple output) was observed, and the fluctuation in peak temperature as the welding torch passed over the thermocouple location was insignificant. It is likely increasing pressure decreases individual bubble size, which simultaneously increases the percentage of area wetted while maintaining convective stirring. The result is more efficient heat transfer and an accelerated cooling rate. The increase in T_{sat} caused by ethylene glycol delays boiling, producing larger hot metal volume compared to water. This larger volume of heated metal coupled with the lower thermal conductivity of the glycol solution reduces the cooling rate.

In equilibrium conditions, the temperature of the internal pipe wall surface will be the liquid T_{sat} when nucleate boiling occurs. However, real situations involve nonequilibrium conditions in which the interior wall surface temperature T_s is greater than the liquid T_{sat}. Surface conditions on the pipe wall, as well as surface tension and latent heat of the liquid, affect the heat transfer process, along with variations in other liquid properties (Ref. 4). In the case of a static liquid, vapor formation in the liquid is called pool boiling, which is differentiated from flow boiling, when the liquid is moving. When the bulk liquid temperature is at T_{sat}, the pool boiling process is called saturated boiling, and, for the case when the bulk liquid temperature is below T_{sat}, it is called subcooled boiling. The latter case describes the experimental conditions in this work.

The heat input comparison between the SMAW and GTAW processes demonstrated the heat inputs for the given experimental setup were somewhat different from the usual values quoted in the welding literature. The arc efficiency of the GTAW process was just over 60% (~40% in the literature), and the SMAW process varied between 75% at high voltage to 85% at lower voltage, thus averaging 80% (~70% in literature). Therefore, for the limited results, the GTAW process is about 75% as efficient as SMAW in arc heat transfer. This is close enough to provide some confidence in the working fluid experiments conducted using the GTAW process, but also indicates any experimental configuration used to achieve similar results to this work should calibrate the GTAW runs with the desired SMAW/FCAW/GMAW (or other) process conditions desired.

Only a start on using different working fluids for weld assessment on active pipelines has been accomplished here. Mixtures of ethylene glycol of varying ratios with water may allow more control over cooling rates, and liquids with other physical characteristics involving T_{sat}, thermal conductivity and viscosity could provide even wider variations in cooling conditions. For example, diethylene glycol has a lower thermal conductivity and higher T_{sat} (Ref. 5) and will be a consideration for further research. The effect of liquid viscosity has not been addressed, and this property may affect convective stirring during heat transfer. The small, contained volume of the test rig, just over 1.2 L (1.5 qt) caused some problems with pressure containment as welding was accomplished. A larger test rig with more sophisticated pressure regulation would be beneficial. With these variables addressed, the controllable cooling rates possible with working fluid changes should open up the possibilities for customized qualification tests for in-service pipelines of any nature. The measured cooling rates for active pipelines determined with the EWI spot heating technique can provide the data for a given hot-tapping situation. The working fluid and pressure conditions in the weld procedure test could then be adjusted to approximate the actual cooling rate as closely as possible, so that hardness readings, for example, are indicative of those to be formed in the final welds.

Shortly after the completion of the experimental program, a need arose for a major Alberta energy producer to conduct a weldment on an active sour gas pipeline in which a shutdown of the pipeline would have resulted in a very significant loss of revenue. Bead-on-pipe single passes on the same 12.8 in. (324 mm) OD x 0.44 in. (11 mm) wall thickness, Grade X-52 pipe material used in the pipeline with water as the working fluid showed preheat alone could not be relied upon to lower the cooling rates sufficiently to facilitate acceptably low hardness levels.

The water-glycol working fluid was therefore employed for procedure qualification testing. Testing was again conducted on the same Grade X-52 pipe material as that used in the pipeline. The nozzle material used for qualification was 4.5 in. (114 mm) OD Schedule 120 A333 Grade 6 carbon steel. Outer wall weld cooling rates at elevated pressures from this experimentation correlated favorably conservative to cooling rates determined through thermocouple plunge testing on weldments conducted on experimental gas loops. The procedure qualification coupons prepared with the water-glycol solution were welded without preheat to simulate the worst-case field condition. The hardness levels measured were all below the NACE-specified 248 HV_{500} for sour service.

Conclusions

1) With water as a working fluid, the peak inner-wall temperature of the pipe section during welding was stable as pressure increased, indicating boiling was suppressed. The peak temperature followed T_{sat} for the liquid. No boiling transition was observed even at high heat inputs.

2) The weld cooling rate could not be controlled with pressure variations with water as the working fluid.

3) Pure ethylene glycol, which has a higher T_{sat} than water, and 50% methanol in water, were uncontrollable as working fluids for weld-zone cooling at low pressures due to dramatic film boiling. This is probably due to the lower T_{sat} of methanol and the lower thermal conductivity and latent heat of ethylene glycol in comparison to water. Pure methanol was not assessed due to explosion and flammability risks.

4) If water is mixed with other liquids of lower T_{sat} (*e.g.,* methanol), the temperature response of the inside wall of the pipe followed the T_{sat} of pure water, except at low pressures. This is likely due to the dominance of the thermal conductivity and specific heat of the water.

5) If water is mixed with other liquids of higher T_{sat} (*e.g.,* ethylene glycol), the peak internal temperature of the pipe is

between the T_{sat} of pure water and the T_{sat} of the other liquid. The outside-wall cooling rate can be decreased by increasing the pressure.

6) The cooling rate for the inside wall of a GTAW welding procedure pressurized pipe test coupon can therefore be varied by judicious choice of the working fluid and internal pressure.

7) Duplicate experiments using low-hydrogen SMAW and GTAW processes in typical pipeline procedural conditions demonstrated the SMAW process is about 25 to 33% more efficient in transferring heat. Therefore, detailed relationships between GTAW and desired SMAW procedural conditions are necessary for procedure and welder qualification using pressure and working fluid modifications to control cooling rates.

8) The variable cooling rates obtained by varying working fluid properties and internal procedure test coupon pressure offer the possibility of approximating real cooling rates of active pipelines in weld procedure testing. This control should provide more realistic qualification testing for hot tapping and increase confidence in weld-zone property values obtained from test coupons, for example, HAZ hardness levels. A field weld on a nozzle-to-pipe weld on an active sour gas pipeline demonstrated that variations in working fluid properties provides useful welding procedure qualification conditions for critical applications.

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